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Symbolic Representation
of
Alternating
Electric Waves

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1985



P.O. BOX 429 ★ GARBERVILLE, CA 95440-0429 ★ U.S.A.

ALGEBRAIC & GRAPHICAL REPRESENTATION OF ALTERNATING ELECTRICAL ENERGY

LET:

e_1 = E.M.F. CONSUMED BY THE CONSUMPTION OF
MAGNETIC LINES OF INDUCTION, OR MAGNETIC ENERGY.

e_{11} = E.M.F. CONSUMED BY THE STORAGE OF MAGNETIC
ENERGY.

i_1 = M.M.F. CONSUMED BY THE CONSUMPTION OF
DIELECTRIC LINES OF INDUCTION, OR DIELECTRIC ENERGY.

i_{11} = M.M.F. CONSUMED BY THE STORAGE OF ~~REA~~
DIELECTRIC ENERGY.

$\dot{E} = e_1 - j e_{11}$, TOTAL E.M.F. CONSUMED BY THE
ALTERNATING CURRENT CIRCUIT, VOLTS COMPLEX.

$\dot{I} = i_1 + j i_{11}$, TOTAL M.M.F. CONSUMED BY THE
ALTERNATING CURRENT CIRCUIT, AMPERES COMPLEX.

WHERE $-j$ IS 90° LEAD AND $+j$ IS 90° LAG

THUS

e_1 = THE VOLTAGE DROP OF EFFECTIVE SERIES RESISTANCE
DUE TO CONSUMPTION OF MAGNETIC ENERGY,

$$e_1 = I_0 R \quad \text{VOLTS, REAL.} \quad (1)$$

e_{11} = THE VOLTAGE DROP OF EFFECTIVE SERIES REACTANCE
DUE TO STORAGE OF MAGNETIC ENERGY,

$$e_{11} = I_0 X \quad \text{VOLTS, LEADING REACTIVE.} \quad (2)$$

HENCE, THE TOTAL CONSUMPTION OF E.M.F., OR VOLTAGE
DROP IS,

$$\dot{E} = e_1 - j e_{11} \quad \text{VOLTS, COMPLEX} \quad (3)$$

$$\dot{E} = I_0 (R - jX) \quad (4)$$

$$\dot{E} = I_0 Z \quad (5)$$

Z IS THE EFFECTIVE SERIES IMPEDANCE OF THE
A.C. CIRCUIT.

THE E.M.F. MEASURED BY A VOLTMETER ACROSS Z IS

$$E_o = |\vec{E}| = \sqrt{e_1^2 + e_{11}^2} \quad \text{VOLTS} \quad (6)$$

i_1 = THE CURRENT DROP OF EFFECTIVE SHUNT CONDUCTANCE DUE TO CONSUMPTION OF DIELECTRIC ENERGY,

$$i_1 = E_o G \quad \text{AMPERES, REAL.} \quad (7)$$

i_{11} = THE CURRENT DROP OF EFFECTIVE SHUNT SUCCEPTANCE DUE TO STORAGE OF DIELECTRIC ENERGY,

$$i_{11} = E_o B \quad \text{AMPERES, LAGGING REACTIVE.} \quad (8)$$

HENCE, THE TOTAL CONSUMPTION OF M.M.F., OR CURRENT DROP IS,

$$\vec{I} = i_1 + j i_{11} \quad \text{AMPERES, COMPLEX} \quad (9)$$

$$\vec{I} = E_o (G + jB) \quad (10)$$

$$\vec{I} = E_o Y \quad (11)$$

Y IS THE EFFECTIVE SHUNT ADMITTANCE OF THE A.C. CIRCUIT.

THE CURRENT MEASURED BY AN AMMETER THRU Y
IS,

$$I = |\dot{I}| = \sqrt{i_1^2 + i_2^2} \quad \text{AMPERES} \quad (4)$$

BECAUSE, IN ANY ALTERNATING CURRENT CIRCUIT,
THE MAGNETIC ENERGY IS DISCHARGING DURING THE
TIME IN WHICH THE ^{DIELECTRIC} MAGNETIC ENERGY IS CHARGING,
THE E.M.F. PRODUCED BY THE DISCHARGE OF MAGNETIC
ENERGY IS IN PHASE OPPOSITION AND ROTATING IN
OPPOSITE DIRECTION TO THE M.M.F. ~~BE~~ CONSUMED BY
THE CHARGE OF DIELECTRIC ENERGY.

THUS

$-j e_1$ REPRESENTS CLOCKWISE ROTATION OF
E.M.F. e_1

AND

$+j i_1$ REPRESENTS COUNTER CLOCKWISE ROTATION
OF M.M.F. i_1

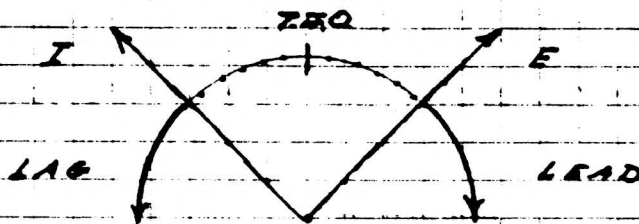
THE EFFECTIVE VALUES OF IMPEDANCE Z AND ADMITTANCE Y CAN ONLY BE DIRECTLY TAKEN FROM MEASUREMENT OF THE CIRCUIT CONSTANTS IF THE EFFECTIVE VELOCITY OF THE A.C. WAVE IS THAT OF LIGHT. IN MANY ELECTRICAL NETWORKS THE VELOCITY IS MUCH DIFFERENT THAN THE VELOCITY OF LIGHT DUE TO THE EXISTANCE OF TRANSVERSE AND LONGITUDINAL ENERGY FLOW.

THIS, THE CIRCUIT CONSTANTS R , G , X , AND B MUST BE MULTIPLIED BY ~~THE~~ A WAVE FACTOR THAT REPRESENTS THE RATIO OF TRANSVERSE TO LONGITUDINAL ENERGY FLOW. THE DERIVATION OF THIS WAVE FACTOR IS BEYOND THE SCOPE OF THIS PAPER AND THE CIRCUIT CONSTANTS R , G , X , B WILL BE THOSE OF THE ELECTROMAGNETIC FIELD RELATIONSHIPS INVOLVED AND NOT THE CONVENTIONAL SCHEMATIC REPRESENTATION OF THE A.C. CIRCUIT.

SINCE THE ALTERNATING POWER IS THE PRODUCT OF CLOCKWISE ROTATION VECTOR $\dot{E}$, AND COUNTERCLOCKWISE ROTATION VECTOR $\dot{I}$, THAT IS $\dot{E}$ & $\dot{I}$ ROTATING IN OPPOSITE DIRECTIONS, THE POWER ROTATES AT TWICE THE FREQUENCY OF $\dot{E}$ OR $\dot{I}$.

THE PHYSICAL MEANING IS, IF AN INCANDESCENT LAMP, WHICH THE BRILLIANCE OF IS A REPRESENTATION OF ELECTRIC POWER, IS CONNECTED TO A SOURCE OF ALTERNATING E.M.F., THE LAMP GLOWS WITH THE SAME BRILLIANCE ON THE POSITIVE AND NEGATIVE HALF CYCLES OF THE E.M.F. . THUS THE BRILLIANCE OF THE LAMP PULSATES AT TWICE THE FREQUENCY OF THE E.M.F. OR CURRENT.

FOR THE PROPER UNDERSTANDING OF ALTERNATING ELECTRIC POWER, IT IS OF IMPORTANCE TO INVESTIGATE THE PRODUCT OF THE OPPOSITE ROTATION VECTORS $\dot{E}$ AND $\dot{I}$.



ALGEBRAICALLY, IT IS:

$$\dot{P} = \dot{E} \dot{I}$$

VOLTAMPERES COMPLEX

$$\dot{P} = (e_1 - j e_2) (i_1 + j i_2)$$

$$= e_1 i_1 + j e_1 i_2 - j e_2 i_1 - j^2 e_2 i_2$$

SINCE THE FACTOR $-j^2$ REPRESENTS 360°
ROTATION

$$-j^2 = +1$$

HENCE

$$\dot{P} = \dot{E} \dot{I} = (e_1 i_1 + e_2 i_2) + j (e_1 i_2 - e_2 i_1) \quad (15)$$

THE PRODUCT $\dot{P} = \dot{E} \dot{I}$ CONSISTS OF TWO PARTS:

THE REAL PART OF USEFULL ENERGY FLOW

$$\rightarrow P_1 = (e_1 i_1 + e_2 i_2) \quad \text{WATTS} \quad (16)$$

THE IMAGINARY PART OF REACTIVE ENERGY FLOW

$$\rightarrow P_2 = (e_1 i_2 - e_2 i_1) \quad \text{VARS} \quad (17)$$

THE REAL PART WILL BE DISTINGUISHED BY THE SUBSCRIPT 1, THE IMAGINARY PART BY THE SUBSCRIPT j .

THUS, THE TOTAL POWER OF THE A.C. CIRCUIT, $\dot{P}$, IS IN SYMBOLIC REPRESENTATION,

$$\dot{P} = P_1 + P_j \quad \text{VOLTAMPERES COMPLEX} \quad (18)$$

JUST AS THE SYMBOLIC REPRESENTATION OF VOLTAGE AND CURRENT AS COMPLEX QUANTITIES DOES NOT ONLY GIVE THE MERE INTENSITY BUT ALSO THE DIRECTION, OR PHASE

$$\dot{I} = i_1 + j i_2 \quad \text{VECTOREAL AMPERES}$$

OF MAGNITUDE (AS READ ON AMMETER SCALE)

$$I = |\dot{I}| = \sqrt{i_1^2 + i_2^2} \quad \text{ABSOLUTE AMPERES}$$

AND DIRECTION OR PHASE ANGLE

$$\theta = \tan^{-1} \frac{i_2}{i_1} \quad \text{RADIAN}$$

SO DOES THE DOUBLE FREQUENCY VECTOR PRODUCT $\dot{E}\dot{I}$ DENOTE MORE THAN THE MERE POWER AS DETERMINED BY THE PRODUCT OF VOLTMETER AND AMMETER READINGS, BY GIVING ITS TWO COMPONENTS;

$$P_1 = (e_1 i_1 + e_2 i_2) \quad \text{WATTS} \quad (16)$$

$$P_2 = (e_1 i_2 - e_2 i_1) \quad \text{VARS} \quad (17)$$

THE TRUE ENERGY VOLTAMPERES AND THE REACTIVE ENERGY VOLTAMPERES RESPECTIVELY.

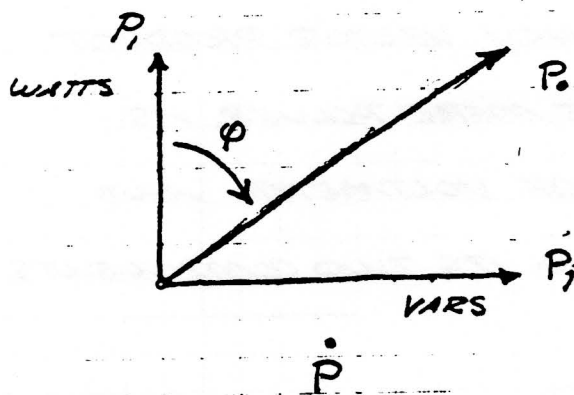
HENCE,

$$\dot{P} = \dot{E}\dot{I} = P_1 + P_2 \quad \text{VECTORIAL V.A.}$$

$$P_0 = EI = \sqrt{P_1^2 + P_2^2} \quad \text{ABSOLUTE V.A. (18a)}$$

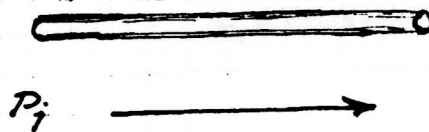
$$\phi = \tan^{-1} \frac{P_2}{P_1} \quad \text{RADIAN}$$

THAT IS, THE TRUE POWER P_1 , AND THE REACTIVE POWER P_2 ARE THE TWO RECTANGULAR COMPONENTS OF THE APPARENT POWER P_0 , WHERE P_0 IS THE PRODUCT OF THE VOLTMETER AND AMMETER READINGS.

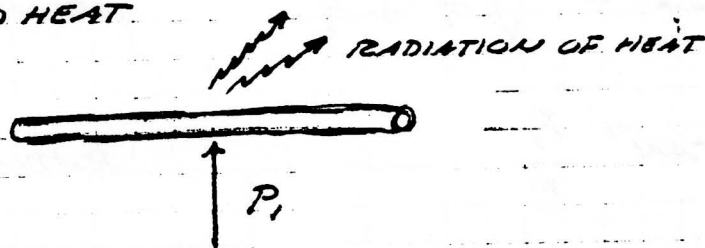


COMPLEX VOLTAMPERES

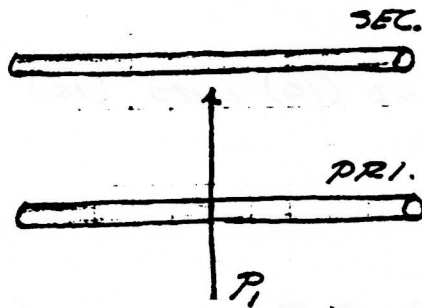
AN APPROXIMATE PHYSICAL REPRESENTATION IS, THE REACTIVE POWER FLOWS ALONG THE AXIS OF THE CONDUCTOR,



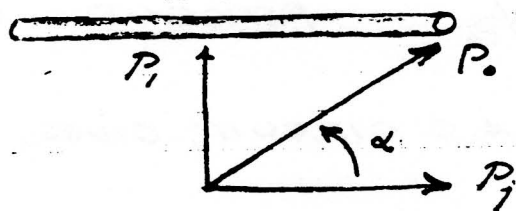
THE REAL POWER FLOWS INTO THE CONDUCTOR AND IS CONVERTED TO HEAT.



OR THE REAL POWER IS DELIVERED TO AN ADJACENT CONDUCTOR, SUCH AS THE ROTOR WINDING OF A MOTOR OR A SECONDARY WINDING OF A TRANSFORMER.



THUS, IN THE FLOW OF POWER ALONG THE CONDUCTOR, A CERTAIN AMOUNT DRAGS INTO THE CONDUCTOR WHERE IT IS CONVERTED INTO HEAT, OR CARRIED OFF TO ANOTHER CONDUCTOR VIA MUTUAL INDUCTION



α = ANGLE OF DRAG

HENCE, THE REACTIVE POWER P_r IS THE CARRIER OF ELECTROMAGNETIC ENERGY, AND THE REAL POWER IS THAT TAKEN OFF TO THE SIDE TO PERFORM USEFUL WORK. THUS THE REACTIVE POWER IS AS IMPORTANT AS THE REAL POWER IN AN ELECTRIC CIRCUIT SINCE WITHOUT IT ENERGY CANNOT BE CONVEYED. THIS IS ILLUSTRATED BY THE FACT THAT THE POWER FACTOR OF A GOOD TRANSMISSION LINE IS ZERO.

SUBSTITUTING EQUATIONS (4) AND (10) INTO (16)
GIVES THE REAL POWER AS,

$$P_r = (e_r i_r + e_m i_m) \quad P_a = E_o I_o \quad (16)$$

$$\left[= P_o (RG + XB) \right]^* \quad \text{WATTS} \quad (19)$$

AND DENOTING

$$\left[a = (RG + XB) \right] \quad \text{PERCENT} \quad (20)$$

$$a = \cos \theta = P_r / P_o \quad \text{PERCENT} \quad (21)$$

AS THE POWER FACTOR OF THE A.C. CIRCUIT, GIVES,

$$P_r = a P_o = a EI \quad \text{WATTS} \quad (22)$$

THAT IS, THE PRODUCT OF THE VOLTMETER READING, E ,
AND OF THE AMMETER READING, I , MULTIPLIED BY THE
POWER FACTOR, a , GIVES THE AMOUNT OF REAL POWER
FLOW, P_r . P_r IS THE RATE AT WHICH ENERGY IS REMOVED
FROM THE ELECTRIC CIRCUIT BY HEAT LOSS OR THE
PRODUCTION OF MECHANICAL ENERGY.

(12)

* FOR TRANSMISSION LINES ONLY

SUBSTITUTING EQUATIONS (4) AND (10) INTO (17)
GIVES THE REACTIVE POWER AS,

$$P_i = (e_1 i_n - e_n i_1) \quad (17)$$

$$\left[= P_o (RB - XG) \right]^* \quad \text{VARS} \quad (23)$$

AND DENOTING

$$b = (RB - XG) \quad \text{PERCENT} \quad (24)$$

$$b = \sin \theta = P_i / P_o \quad \text{PERCENT} \quad (25)$$

AS THE INDUCTION FACTOR OF THE A.C. CIRCUIT, GIVES.

$$P_i = b P_o = b EI \quad \text{VARS} \quad (26)$$

THAT IS, THE PRODUCT OF THE VOLTMETER READING, E ,
AND OF THE AMMETER READING, I , MULTIPLIED BY THE
INDUCTION FACTOR, b , GIVES THE AMOUNT OF REACTIVE
POWER FLOW, P_i . P_i IS THE RATE AT WHICH ENERGY
IS CARRIED ALONG THE ELECTRICAL CIRCUIT BY ^{SELF.} INDUCTION,
OR IF THE CIRCUIT IS AT THE END OF THE LINE, THE RATE
AT WHICH ENERGY IS BOUNCED BACK INTO THE LINE.

(13)

HENCE, THE TOTAL POWER IN TERMS OF EQUATIONS (19) AND (23) IS

$$\dot{P} = P_0 \left[(RG + XB) + j(RB - XB) \right] \quad (27)$$

VOLTAMPERES COMPLEX
I.E.M. WAVE

SUBSTITUTING a AND b GIVES

$$\dot{P} = P_0 (a + jb) \quad (28)$$

OR IN TRIGONOMETRIC FORM

$$\dot{P} = P_0 (\cos \theta + j \sin \theta) \quad (29)$$

THUS

$$\dot{P} = \gamma_0 P_0 \quad \text{VOLTAMPERES COMPLEX} \quad (30)$$

WHERE

$$\gamma_0 = (a + jb) = (\cos \theta + j \sin \theta) \quad (31)$$

$$|\gamma_0| = \sqrt{a^2 + b^2} = 1$$

$$\varphi = \tan^{-1} \frac{b}{a}$$

(14)

THE FACTOR γ_0 IS CALLED THE WAVE FACTOR OF THE A.C. CIRCUIT, AND IS A COMPLEX QUANTITY CONSISTING OF THE REAL PART a , THE CIRCUIT POWER FACTOR, AND THE IMAGINARY PART b , THE CIRCUIT ^{INDUCTIVE} ~~POWER~~ FACTOR. THE MAGNITUDE OF γ_0 IS ALWAYS EQUAL TO UNITY, THAT IS, 100%, AS IT REPRESENTS ALL FACTORS.

SUBSTITUTING INTO (27) ~~AND~~ & DIVIDING OUT POWER,

$$\gamma_0 = (a + jb) \quad \text{PERCENT, COMPLEX} \quad (31)$$

$$\gamma_0 = (R_G + X_B) + j(R_B - X_G) \quad (32)$$

$$\gamma_0 = Z Y \quad \text{PERCENT, COMPLEX} \quad (33)$$

EQUATION (32) IS KNOWN AS THE WAVE EQUATION OF THE A.C. CIRCUIT. THIS EQUATION IS THE FUNDAMENTAL EQUATION FOR THE INVESTIGATION OF ALTERNATING CURRENT PHENOMENA.

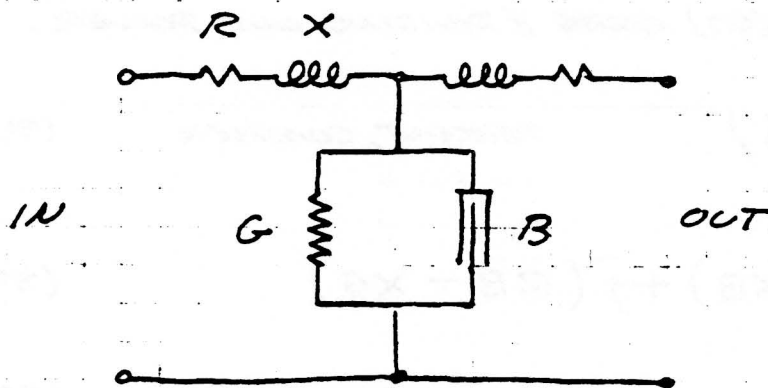
THUS, THE PRODUCT OF THE VOLTMETER READING AND THE AMMETER READING, P_0 , MULTIPLIED BY THE WAVE FACTOR, γ_0 , GIVES THE AMOUNT OF VECTORIAL POWER FLOW, $\dot{P}$.

$$\gamma_0 P_0 = P_i + j P_j$$

^{WAVE}
 BREAKING THE EQUATION DOWN INTO ITS COMPONENTS
 WILL HELP IN THE UNDERSTANDING OF ITS PRACTICAL
 SIGNIFICANCE.

$$\gamma_0 = ZY = (R_G + jX_B) + j(R_B - jX_G)$$

$$= (R - jX)(G + jB)$$



SECTION OF TWO
 WIRE LINE.
 (T.E.M. WAVE)

TOTAL CIRCUIT ELEMENT $\nearrow$, R_G , X_B , R_B , AND X_G .

$$X = \omega L = 2\pi FL \quad \text{OHMS} = \frac{\text{HENRY}}{\text{SECOND}}$$

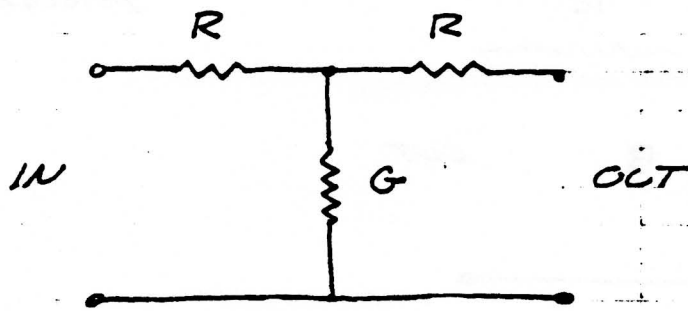
$$B = \omega C = 2\pi FC \quad \text{MHOS} = \frac{\text{FARADS}}{\text{SECOND}}$$

$$\omega = 2\pi F, \text{ ANGULAR VELOCITY OF ROTATION}$$

IN RADIANS PER SECOND

$$F = \text{CYCLES PER SECOND}$$

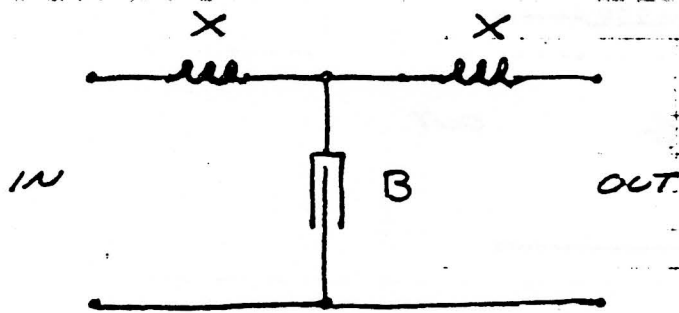
RG



PERCENT

RG IS THE RATE OF ENERGY CONSUMPTION WITH RESPECT TO DISTANCE ALONG THE A.C. CIRCUIT, AND IS INDEPENDENT OF THE FREQUENCY OF THE A.C. WAVE.

XB



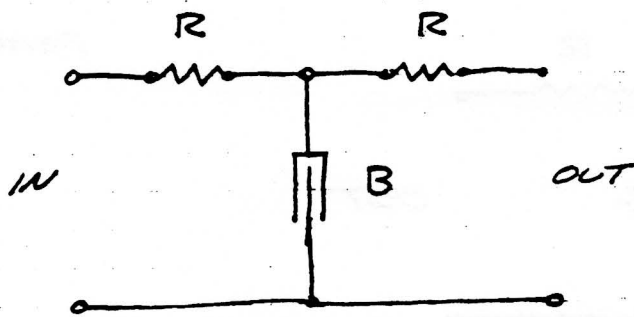
PERCENT

XB IS THE TIME RATE OF ENERGY EXCHANGE BETWEEN THE MAGNETIC FIELDS STORED ENERGY AND THE DIELECTRIC FIELDS STORED ENERGY, THAT IS, THE RATE AT WHICH THE DISCHARGING MAGNETIC FIELD CHARGES THE DIELECTRIC FIELD AND VIS.VIS. THUS XB IS THE NATURAL FREQUENCY OF OSCILLATION OF THE CIRCUIT, AND DETERMINES THE VELOCITY OF THE WAVE ALONG THE CIRCUIT.

(17)

RB

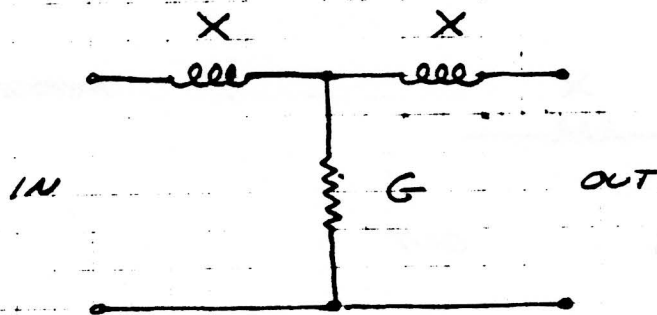
PERCENT



RB IS THE TIME RATE OF THE DRAINING OF DIELECTRIC STORED ENERGY INTO THE CIRCUIT RESISTANCE, AND IS CALLED THE TIME CONSTANT OF DIELECTRIC ENERGY.

XG

PERCENT



XG IS THE TIME RATE OF THE DRAINING OF MAGNETIC STORED ENERGY INTO THE CIRCUIT CONDUCTANCE, AND IS CALLED THE TIME CONSTANT OF MAGNETIC ENERGY.

CONSEQUENTLY, IN ANY ALTERNATING CURRENT CIRCUIT THERE EXIST FOUR DISTINCT FLOWS OF ENERGY:

- + $e_1 i_1$, A FUNCTION OF RG , REPRESENTS THE FLOW OF ENERGY OUT OF THE CIRCUIT, AND IS INDEPENDENT OF THE FREQUENCY OR PHASE OF THE APPLIED A.C. WAVE.
- + $e_{11} i_{11}$, A FUNCTION OF XB , REPRESENTS THE PULSATION OF ENERGY BETWEEN THE MAGNETIC AND DIELECTRIC FIELDS SURROUNDING THE CIRCUIT.
- + $e_1 i_{11}$, A FUNCTION OF RB , REPRESENTS THE FLOW OF ENERGY INTO THE DIELECTRIC FIELD, THRU CIRCUIT RESISTANCE, R .
- $e_{11} i_1$, A FUNCTION OF XG , REPRESENTS THE FLOW OF ENERGY OUT OF THE MAGNETIC FIELD THRU CIRCUIT CONDUCTANCE, G .

SYMBOLIC & GRAPHICAL ANALYSIS
OF SPECIAL CASES

1) THE WATTLSS REACTIVE POWER IS ABSENT, OR
THE TOTAL POWER IS REAL, IF,

$$P_i = 0$$

$$(e, i_{\parallel} - e_{\parallel} i_i) = 0$$

HENCE

$$e, i_{\parallel} = e_{\parallel} i_i$$

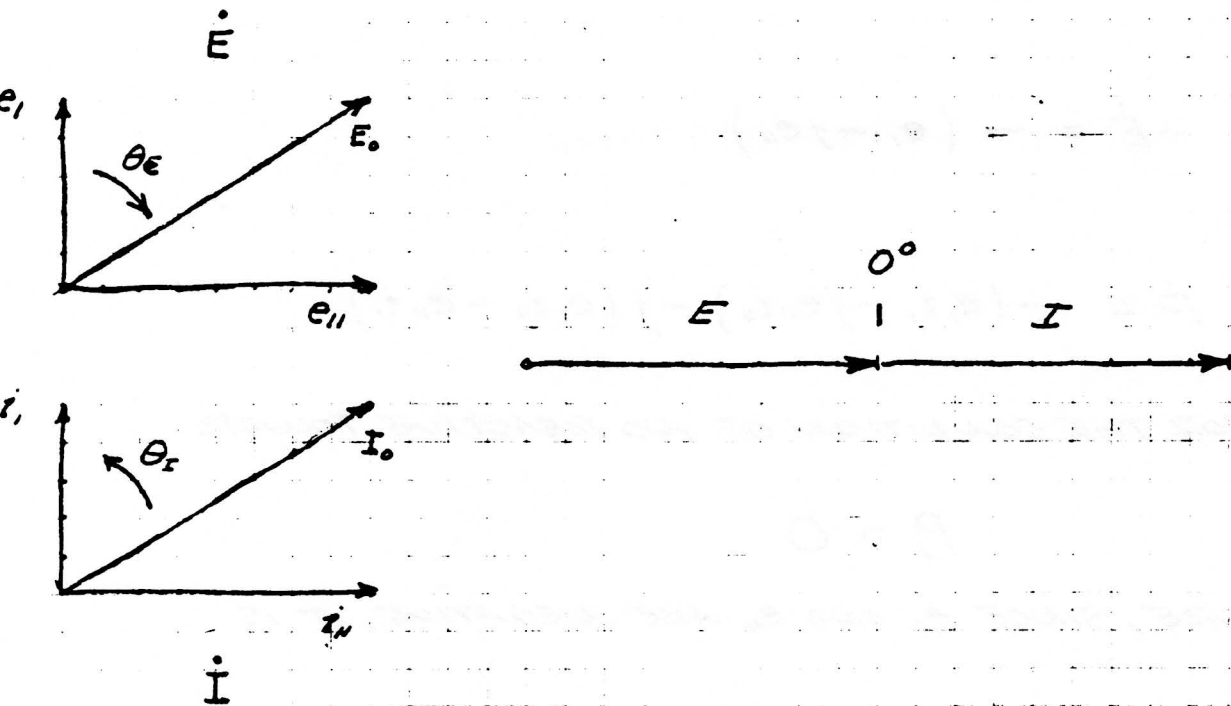
THAT IS, THE RATE OF DIELECTRIC DISSIPATION IS
EQUAL TO THE RATE OF MAGNETIC DISSIPATION OF
ENERGY.

THEREBY

$$\frac{e_{\parallel}}{e_i} = \frac{i_{\parallel}}{i_i}$$

OR

$$\tan(\dot{E}) = \tan(\dot{I})$$



THAT IS, $\dot{E}$ AND $\dot{I}$ ARE IN PHASE CONJUNCTION

SUBSTITUTING $P_f = 0$ INTO THE EQUATION FOR γ_0

GIVES

$$\gamma_0 = (a + jb) = +1 + j0$$

$$\gamma_0 = +1$$

THUS THE WAVE FACTOR BECOMES THE POWER FACTOR, WHICH IS $100\gamma_0$. THE INDUCTION FACTOR IS ZERO.

IF, HOWEVER, THE CIRCUIT PRODUCES MORE REAL ENERGY THAN IT CONSUMES, SUCH AS THE SECONDARY CIRCUIT OF A MOTOR OR TRANSFORMER, OR A SYSTEM INVOLVING CO-GENERATION, THE BACK E.M.F. OF SERIES IMPEDANCE BECOMES FORWARD E.M.F.

$$-\dot{E} = -(e_1 - j e_{11})$$

AND

$$\dot{P} = -(e_1 i_1 - j e_{11} i_{11}) - j (e_1 i_{11} - e_{11} i_1)$$

BUT, FOR THE CONDITION OF NO REACTIVE POWER

$$P_i = 0$$

THEREFORE, SINCE e_1 AND e_{11} ARE NEGATIVE, IT IS

$$-e_1 i_{11} = -e_{11} i_1$$

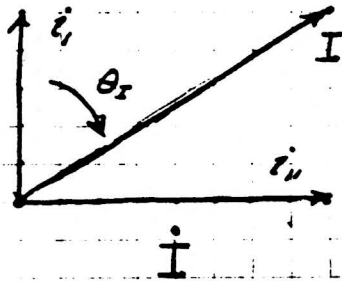
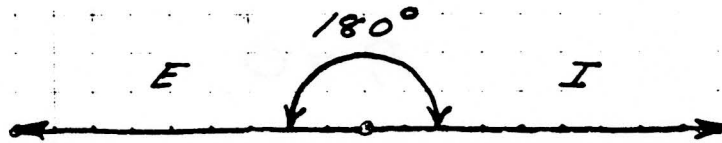
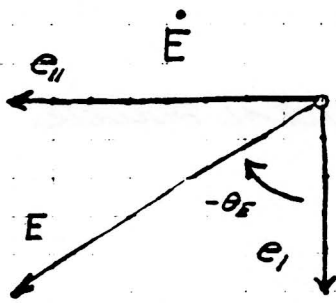
THAT IS, THE RATE OF DIELECTRIC CHARGE IS
EQUAL TO THE RATE OF MAGNETIC CHARGE OF ENERGY.

THEREBY

$$\frac{-e_{11}}{-e_1} = \frac{i_{11}}{i_1}$$

OR

$$\tan(-\dot{E}) = \tan(\dot{I})$$



— THAT IS, $\dot{E}$ AND $\dot{I}$ ARE IN PHASE OPPOSITION.

SUBSTITUTING $P_r = 0$ AND $-P_r$ INTO THE EQUATION FOR γ_0 GIVES

$$\gamma_0 = (a + jb) = -1 + j0$$

$$\gamma_0 = -1$$

THUS THE WAVE FACTOR, WHICH IS THE POWER FACTOR IN THE CASE OF ZERO REACTIVE POWER, NOW IS NEGATIVE 100%. THE INDUCTION FACTOR REMAINS ZERO.

2) THE TRUE POWER IS ABSENT, OR THE TOTAL POWER.
REACTIVE IF,

$$P_r = 0$$

$$(e_1 i_1 + e_{11} i_{11}) = 0$$

HENCE

$$+e_1 i_1 = -e_{11} i_{11}$$

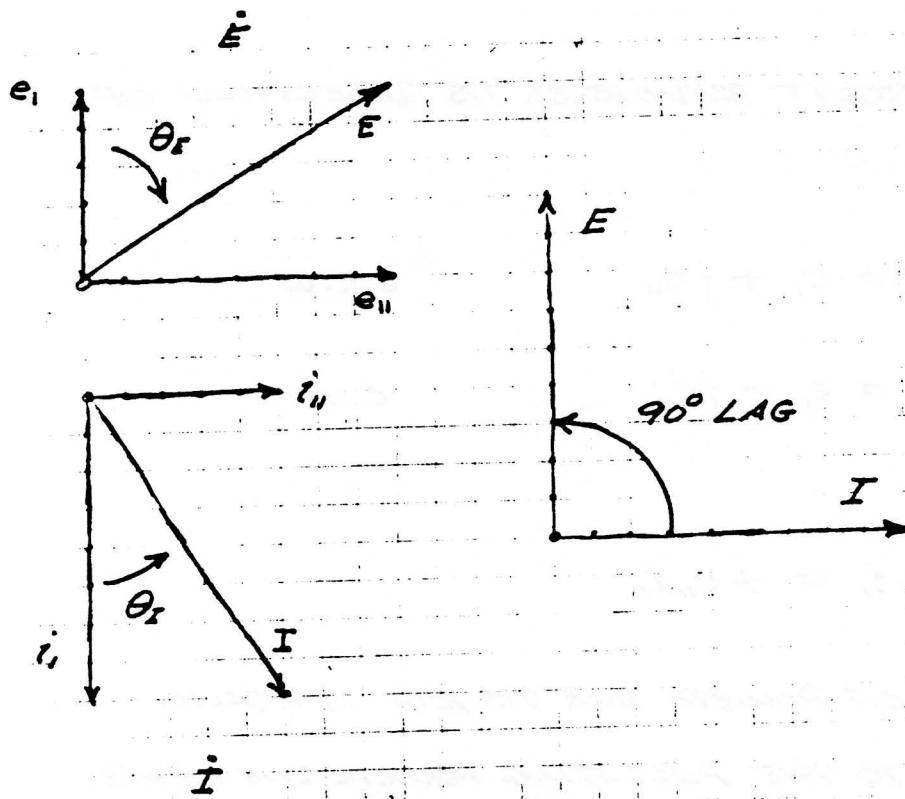
IN AND
THAT IS, THE FLOW OF POWER/OUT OF THE CIRCUIT VIA
RG IS EQUAL AND IN OPPOSITION TO THE FLOW OF
PULSATING STORED ENERGY BETWEEN MAGNETIC AND
DIELECTRIC FORMS.

THUS,

$$\frac{e_{11}}{e_1} = -\frac{i_1}{i_{11}}$$

OR

$$\tan(\dot{E}) = -\cot(\dot{I})$$



THAT IS, $\dot{E}$ AND $\dot{I}$ ARE IN PHASE LAG QUADRATURE.

SUBSTITUTING $P_r = 0$ INTO THE EQUATION FOR γ_0
GIVES

$$\gamma_0 = (a + jb) = 0 + j$$

$$\gamma_0 = +j$$

THUS THE WAVE FACTOR BECOMES THE INDUCTION FACTOR
FOR THE CONDITION OF ZERO REAL POWER, AND IS 100%.
THE POWER FACTOR IS ZERO.

IF, HOWEVER, THE CIRCUIT CONSUMES LESS REACTIVE
POWER THAN IT PRODUCES, SUCH AS WITH CAPACITOR
LOADS, SYNCHRONOUS CONDENSERS, ETC. THE ALTERNATING

WAVE OF THE A.C. CIRCUIT REVERSES ITS DIRECTION OF ROTATION, THAT IS,

$$\dot{E} = e_1 + j e_{11}$$

C.C.W

$$\dot{I} = i_1 - j i_{11}$$

C.W

HENCE

$$- e_1 i_1 = + e_{11} i_{11}$$

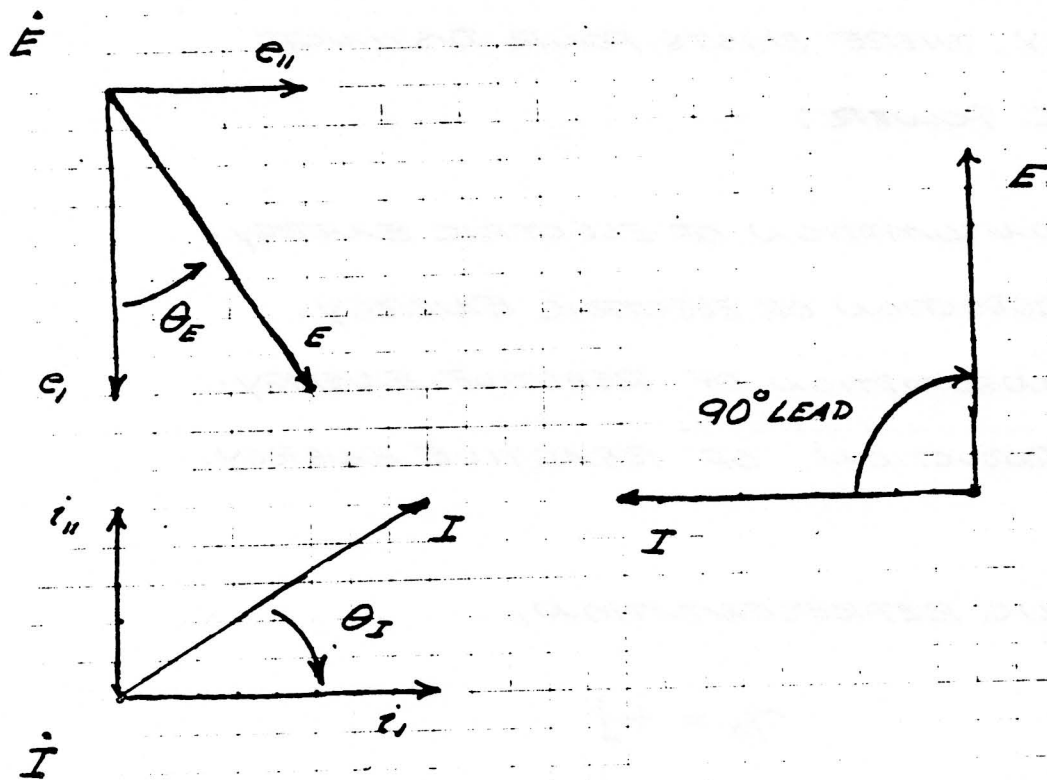
THAT IS, THE FLOW OF POWER DUE TO R_G IS EQUAL AND IN OPPOSITION TO THE PULSATING POWER DUE TO X_B .

THUS

$$- \frac{e_1}{e_{11}} = \frac{i_{11}}{i_1}$$

OR

$$- \cot(\dot{E}) = \tan(\dot{I})$$



— THAT IS, $\dot{E}$ AND $\dot{I}$ ARE IN PHASE LEAD QUADRATURE.

SUBSTITUTING REACTIVE ENERGY PRODUCTION $-P_i$
AND $P_i = 0$ INTO THE EQUATION FOR γ_0 GIVES

$$\gamma_0 = (a + jb) = 0 - j$$

$$\gamma_0 = -j$$

THUS THE WAVE FACTOR, WHICH IS THE INDUCTION FACTOR
FOR THE CONDITION OF ZERO POWER FLOW, IS NEGATIVE
100%. THE POWER FACTOR IS ZERO.

CONSEQUENTLY, THERE EXISTS FOUR DISTINCT CLASSES OF A.C. POWER:

1A) THE CONSUMPTION OF ELECTRIC ENERGY.

1B) THE PRODUCTION OF ELECTRIC ENERGY.

2A) THE CONSUMPTION OF REACTIVE ENERGY.

2B) THE PRODUCTION OF REACTIVE ENERGY.

OR IN SYMBOLIC REPRESENTATION,

$$\gamma_0 = +1$$

$$\gamma_0 = +j$$

$$\gamma_0 = -1$$

$$\gamma_0 = -j$$

REAL

REACTIVE

AND THE POWER IS,

$$\dot{P} = +P_r$$

$$\dot{P} = +P_i$$

$$\dot{P} = -P_r$$

$$\dot{P} = -P_i$$

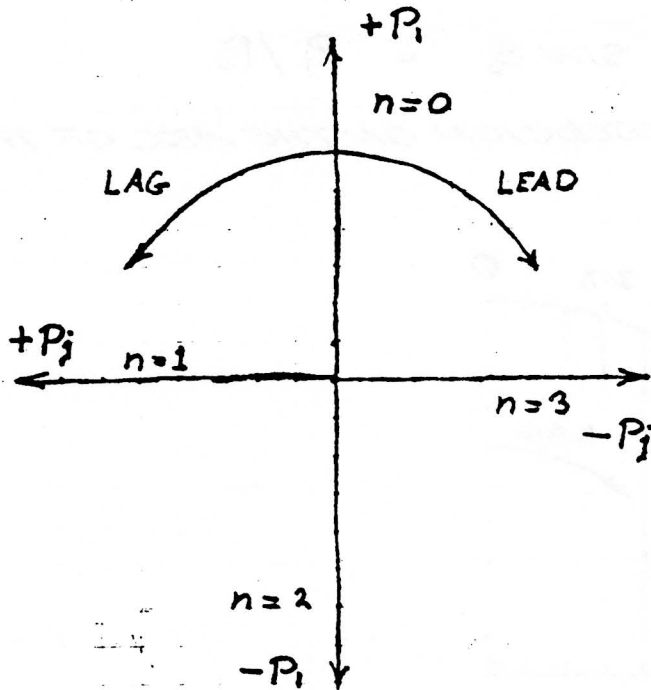
HENCE γ_0 IS A RESULT OF

$$\sqrt[n]{+1} = k^n = \pm 1, \pm j$$

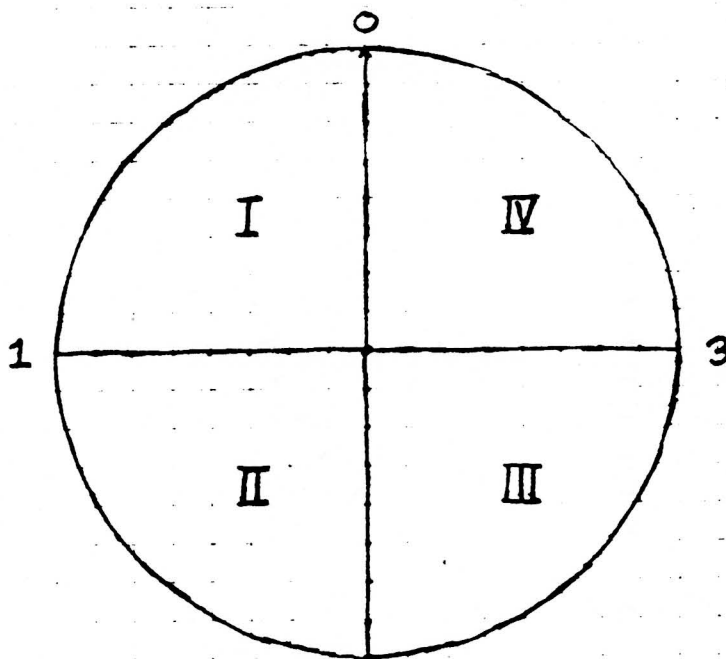
k^n IS THE QUADRANT OPERATOR.

GRAPHICALLY, IT IS,

$$K^n =$$



THUS, FOUR QUADRANTS,



↑
ACTIVE ENERGY
CONSUMPTION

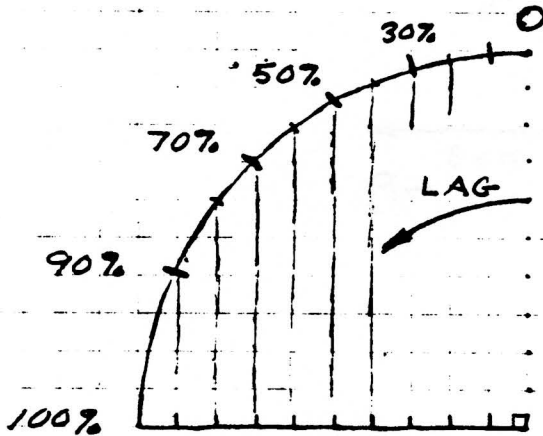
ACTIVE ENERGY
PRODUCTION
↓

← REACTIVE ENERGY PRODUCTION 2 REACTIVE ENERGY PRODUCTION →

THE INDUCTION FACTOR OF THE CIRCUIT IS GIVEN BY

$$\sin \theta_0 = P_i / P_0$$

AND IS GIVEN BY PROJECTION ON THE ARC OF THE QUADRANT



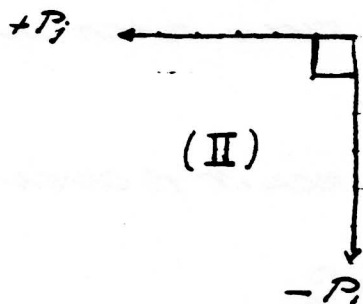
THUS THE CORRESPONDING INDUCTION METER SCALE SECTION.

NOTE: NO PAGE 31

QUADRANT II

$$\theta_0 = j^2 + \varphi$$

$$\gamma_0 = -(a) + j(b)$$

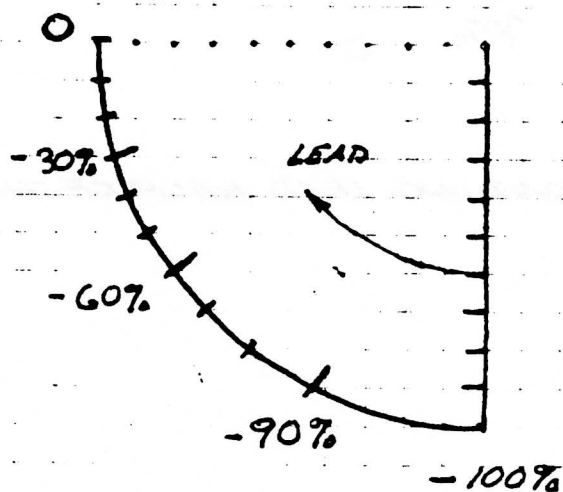


THIS QUADRANT REPRESENTS PRODUCTION OF REAL ENERGY AND THE CONSUMPTION OF REACTIVE ENERGY, SUCH AS THE COMBINATION OF INDUCED FORWARD E.M.F. AND REACTIVE BACK E.M.F. OF AN ALTERNATOR COIL.

THE POWER FACTOR IS GIVEN BY

$$-\sin \theta_0 = -P_r / +P_i$$

AND PROJECTION OF THE REAL POWER UPON THE ARC OF THE QUADRANT GIVES,

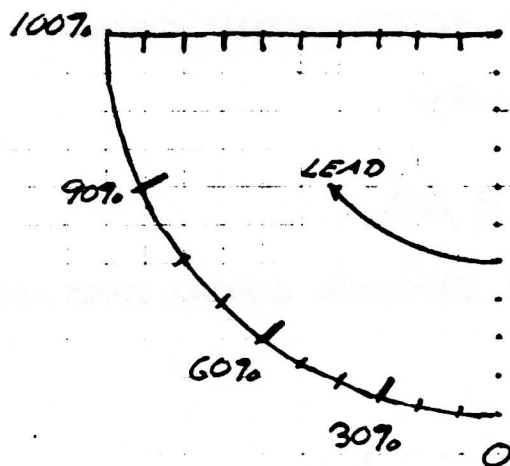


THIS PORTION OF THE CURVE IS USUALLY NOT MARKED BY DIVISIONS ON THE POWER FACTOR METER SINCE IT REPRESENTS A REVERSAL OF POWER FLOW BACK INTO THE SOURCE OF ELECTRICAL ENERGY.

THE INDUCTION FACTOR OF THE CIRCUIT IS GIVEN BY

$$\cos \theta_0 = \frac{P_i}{P_0} = +P_i / -P_0$$

AND PROJECTION OF THE REACTIVE POWER UPON THE ARC OF THE QUADRANT GIVES,

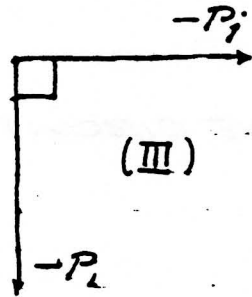


THUS THE CORRESPONDING LEAD HALF OF THE INDUCTION FACTOR METER SCALE

QUADRANT III

$$\theta_0 = j^2 + \phi$$

$$\gamma_0 = -(a + jb)$$

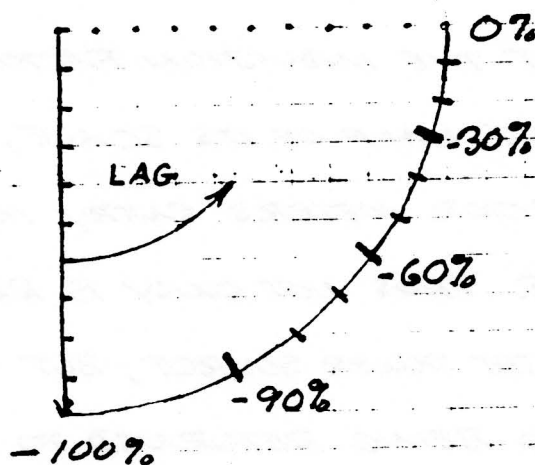


THIS QUADRANT REPRESENTS THE PRODUCTION OF BOTH REAL AND REACTIVE ENERGY, SUCH AS THE COMBINATION OF AN ALTERNATOR WITH NEGLIGIBLE SELF INDUCTION AND A CAPACITOR.

THE POWER FACTOR IS GIVEN BY

$$\cos \theta_0 = -P_i / -P_r = \cos \theta_0$$

AND THE PROJECTION OF THE REAL POWER UPON THE ARC OF THE QUADRANT GIVES,

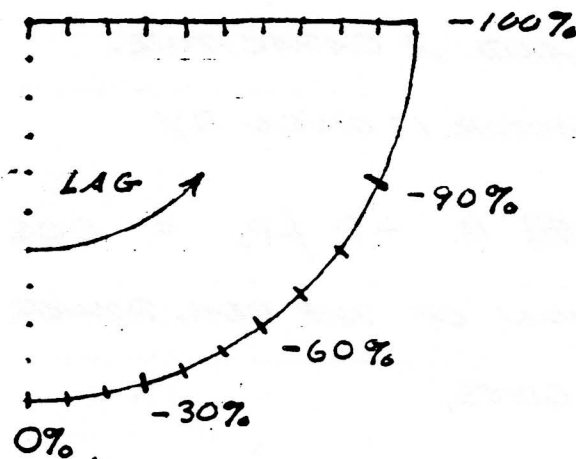


THIS PORTION OF THE CURVE ALSO REPRESENTS REVERSED POWER FLOW BACK INTO THE SOURCE OF ELECTRICAL ENERGY AS DOES QUADRANT II, THUS ALSO IS LEFT UNMARKED ON MOST METER SCALES

THE INDUCTION FACTOR OF THE CIRCUIT IS GIVEN BY

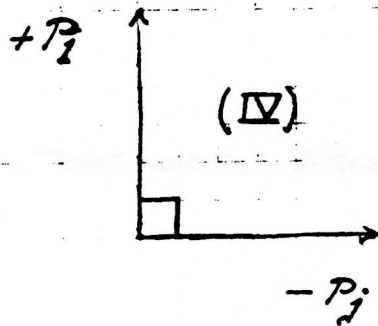
$$-\sin \theta_0 = -P_i / P_0$$

AND THE PROJECTION OF THE REACTIVE POWER UPON THE ARC OF THE QUADRANT GIVES,



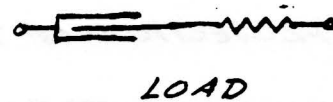
IT CAN BE SEEN THAT THE INDUCTION FACTOR HAS NOW ENTERED THE NEGATIVE HALF OF ITS SCALE, 90° LATER THAN THE POWER FACTOR METERS ENTRY INTO ITS NEGATIVE HALF SCALE. THUS NOT ONLY IS REAL ENERGY BEING RETURNED TO THE POWER SOURCE, BUT REACTIVE ENERGY IS NOW ALSO BEING RETURNED TO THE SOURCE OF POWER.

QUADRANT IV



$$\theta_o = j^3 - \phi = -(j^3 + \phi)$$

$$\gamma_o = (a - jb)$$

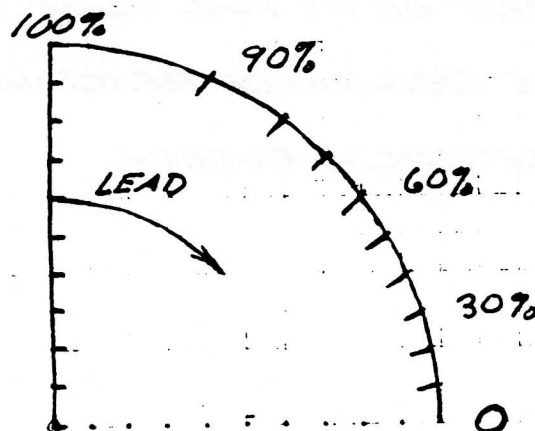


THIS QUADRANT REPRESENTS THE CONSUMPTION OF REAL ENERGY AND THE PRODUCTION OF REACTIVE ENERGY, SUCH AS A SYNCHRONOUS CONDENSER.

THE POWER FACTOR IS GIVEN BY,

$$\sin \theta_o = +P_i / +P_o$$

AND THE PROJECTION OF THE REAL POWER UPON THE ARC OF THE ~~UNIT~~ QUADRANT GIVES,

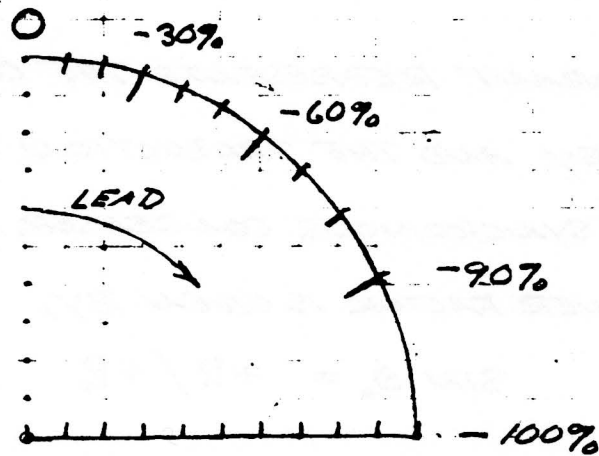


THIS CURVE WILL BE RECOGNIZED AS THE LEAD PORTION OF THE POWER FACTOR SCALE.

THE INDUCTION FACTOR OF THE CIRCUIT IS GIVEN BY,

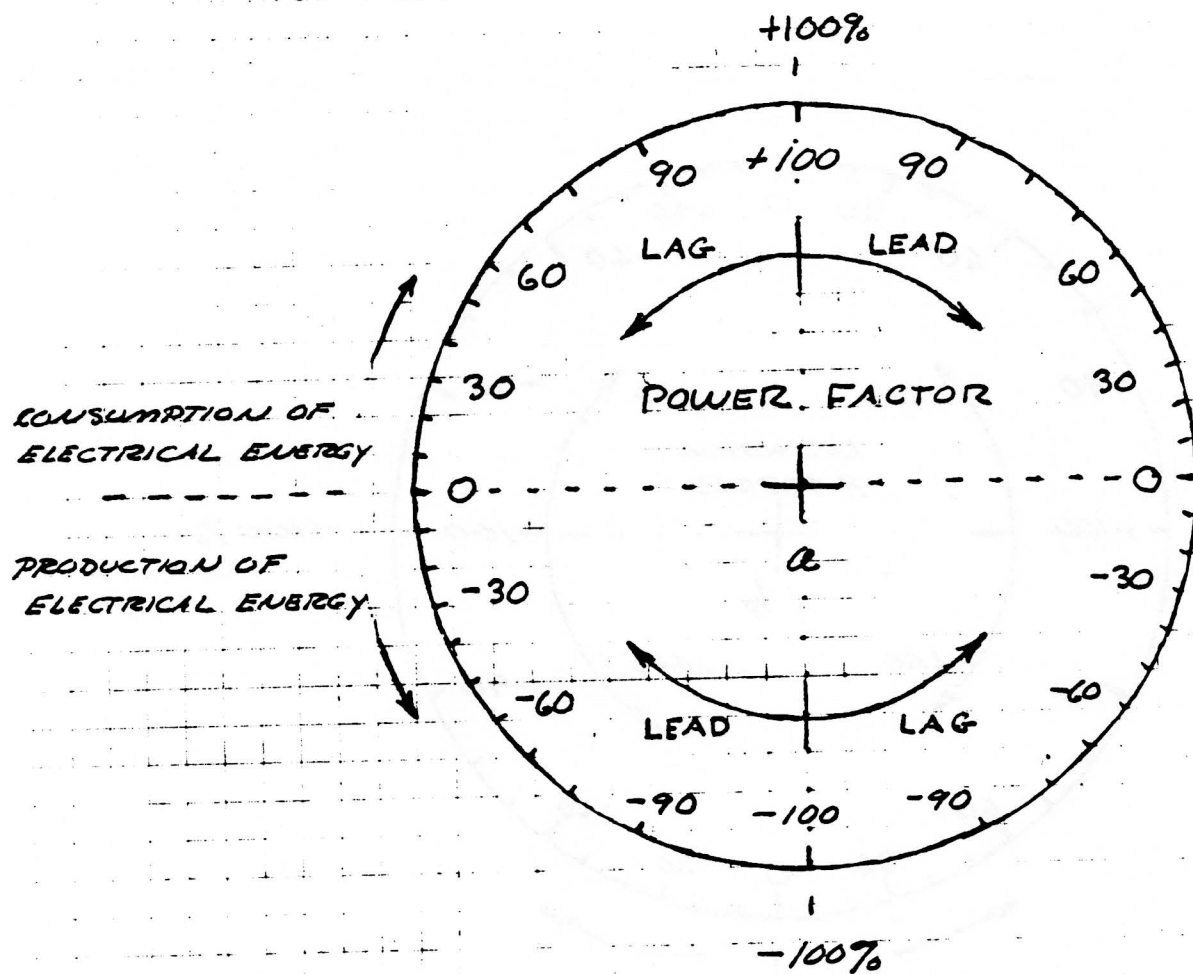
$$\cos \theta_0 = -P_i / P_0$$

AND THE PROJECTION OF THE REACTIVE POWER UPON THE ARC OF THE QUADRANT GIVES



THUS, THE INDUCTION FACTOR SCALE IS IN THE SECOND NEGATIVE QUADRANT OF ITS FULL SCALE. THEREFORE, IT IS INDICATING THE RETURN OF REACTIVE ENERGY INTO THE SOURCE OF ELECTRICAL ENERGY.

HAVING COMPLETED A COMPLETE CYCLE OF ALTERNATING ELECTRICAL ENERGY, THE COMPLETE METER SCALES ARE AS FOLLOWS:



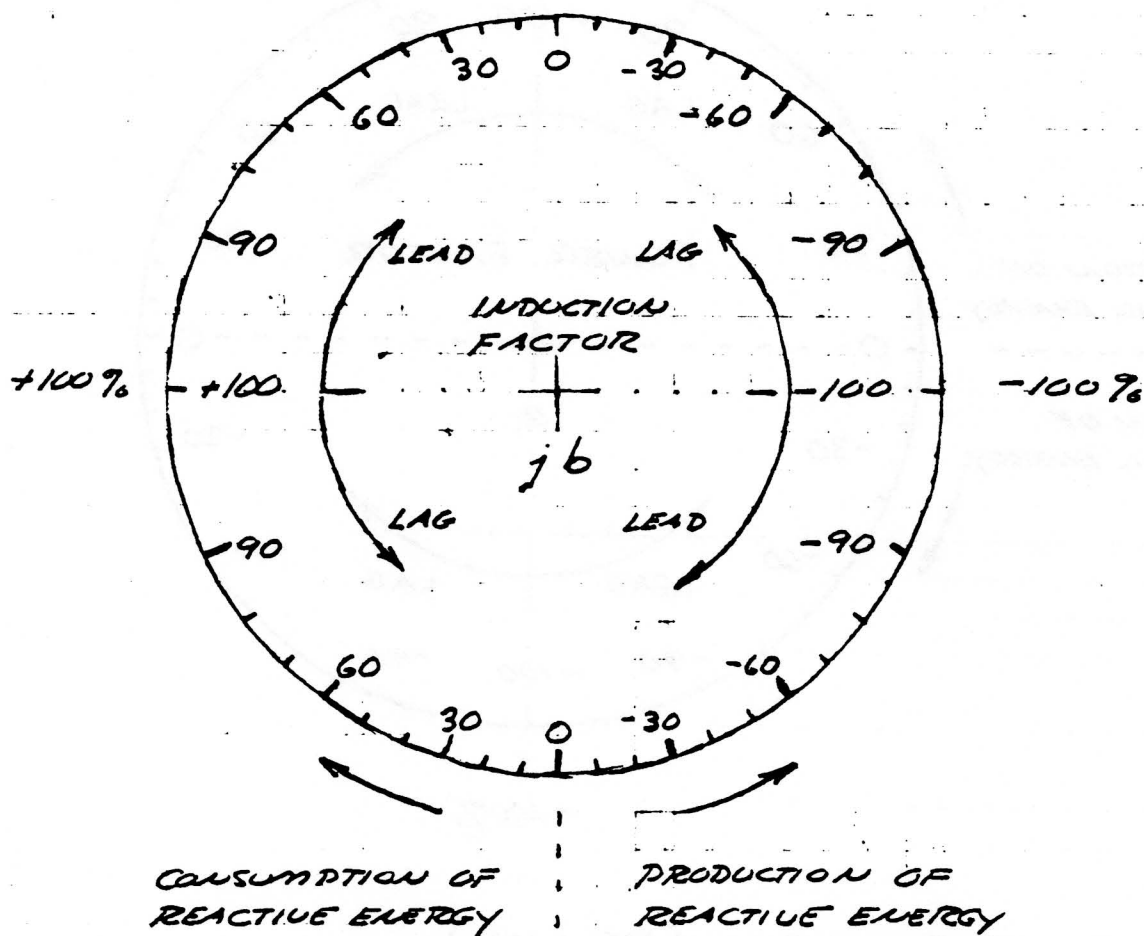
$$\text{POWER FACTOR} = \alpha = (R_G + X_B)$$

$$= P_1 / P_0$$

RATIO OF REAL (ACTIVE) POWER TO APPARENT POWER.

$$\begin{aligned}\text{INDUCTION FACTOR} &= j b = j(R_B - X_G) \\ &= j P_i / P_o\end{aligned}$$

RATIO OF REACTIVE POWER TO APPARENT POWER.



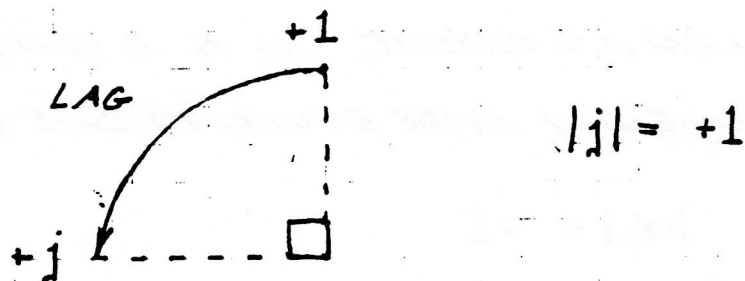
HENCE, THE PHYSICAL SIGNIFICANCE OF THE EQUATION OF THE ELECTRIC WAVE,

$$\gamma_0 = a + jb = \cos \theta + j \sin \theta$$

a IS THE READING TAKEN FROM THE POWER FACTOR MEASUREMENT OF THE CIRCUIT

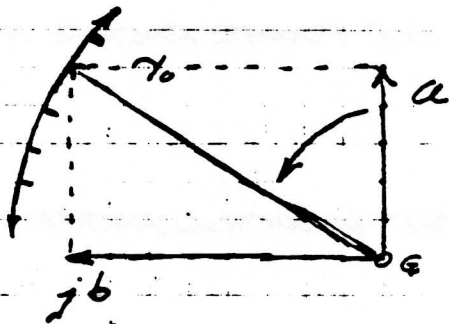
b IS THE READING TAKEN FROM THE INDUCTION FACTOR MEASUREMENT OF THE CIRCUIT.

$+j$ IS THAT THE INDUCTION FACTOR SCALE IS AT RIGHT ANGLES TO THE POWER FACTOR SCALE,



MULTIPLICATION BY $+j$ MEANS TO ROTATE ONE QUARTER CYCLE (ONE QUADRANT) IN THE LAG (C.C.W.) DIRECTION, AND THE MAGNITUDE OF $+j$ IS EQUAL TO $+1$.

THUS γ_0 IS A VECTOR CONSISTING OF A VERTICAL COMPONENT a , THE POWER FACTOR OF THE A.C. CIRCUIT, AND A HORIZONTAL COMPONENT, b , THE INDUCTION FACTOR OF THE CIRCUIT,



(NON ROTATIVE VECTOR
WITH LENGTH PULSATING
AT $2F$)

SINCE THE LENGTH OF THE VECTOR γ_0 IS THE RADIUS OF A CIRCLE HAVING NO RELATION TO THE A.C. CIRCUIT, BUT IS AN ARBITRARY LENGTH, SUCH AS THE DIAMETER OF METER SCALE, GRAPH PAPER SIZE, ETC., AND SINCE γ_0 IS 100% FOR ALL CONDITIONS IN AN A.C. CIRCUIT, γ_0 IS A CONSTANT AND IS MOST CONVENIENTLY MADE EQUAL TO ONE (+1)

$$|\gamma_0| = +1$$

AND IT FOLLOWS THAT

$$a^2 + b^2 = 1$$

$$\sin^2 \theta + \cos^2 \theta = 1$$

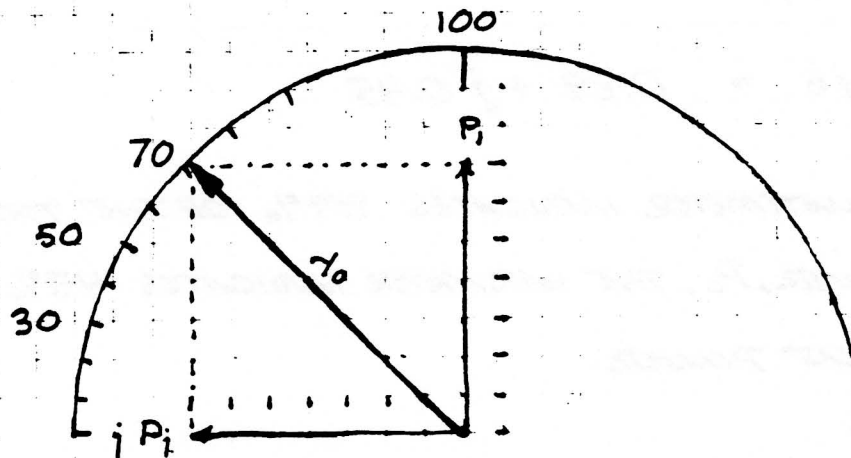
THEREBY,

$$\alpha = \pm \sqrt{1 - b^2} \quad , \text{ POWER FACTOR}$$

$$b = \pm \sqrt{1 - \alpha^2} \quad , \text{ INDUCTION FACTOR}$$

THAT IS, IF NO INDUCTION FACTOR METER EXISTS, THE INDUCTION FACTOR MAY BE CALCULATED FROM THE POWER FACTOR, SINCE THE MAGNITUDE OF THE WAVE FACTOR IS ALWAYS 100% OR 1.

THUS, THE WAVE FACTOR γ_0 OF THE A.C. CIRCUIT POINTS THE DIRECTION OF POWER FLOW WITH RESPECT TO THE A.C. CYCLE.



POWER FACTOR

EXAMPLES

- 1) AN INDUCTION MOTOR IS DELIVERING 12.5 HORSEPOWER (10KW) TO A MECHANICAL LOAD. THE REACTIVE ENERGY OF THE MOTOR'S UNUSED MAGNETIC FLUX IS 5KW (6.25HP).

HENCE

$$P_1 = 10\text{KW} \quad , \quad \text{WATTMETER}$$

$$P_j = 5\text{KW} \quad , \quad \text{VAR METER}$$

$$P_o = \sqrt{10^2 + 5^2} = 11.2 \text{ KW} \quad , \quad \text{VOLTMETER} \times \text{AMMETER}$$

$$a = 89\%$$

POWER FACTOR METER

$$b = 45\%$$

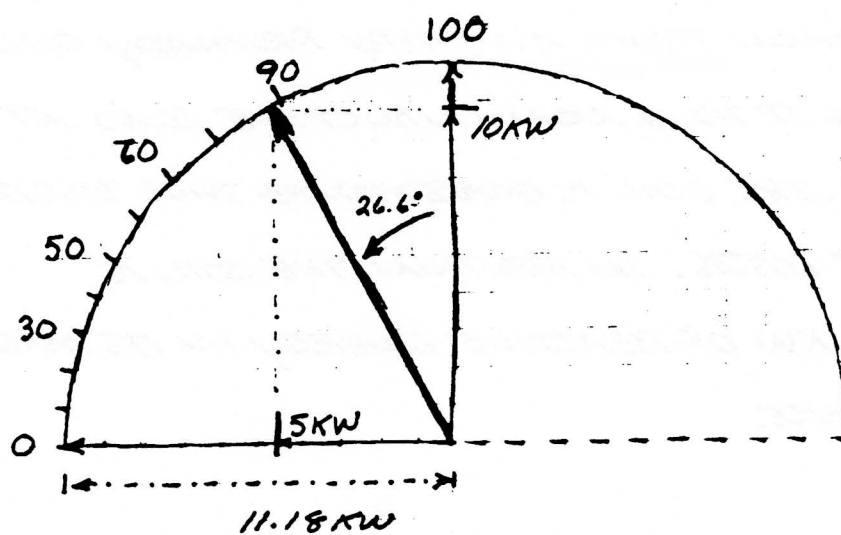
INDUCTION FACTOR METER

$$\theta_o = \tan^{-1} P_j / P_1 = 26.6^\circ \text{ LAG}$$

$$\gamma_o = a + jb = 0.89 + j0.45$$

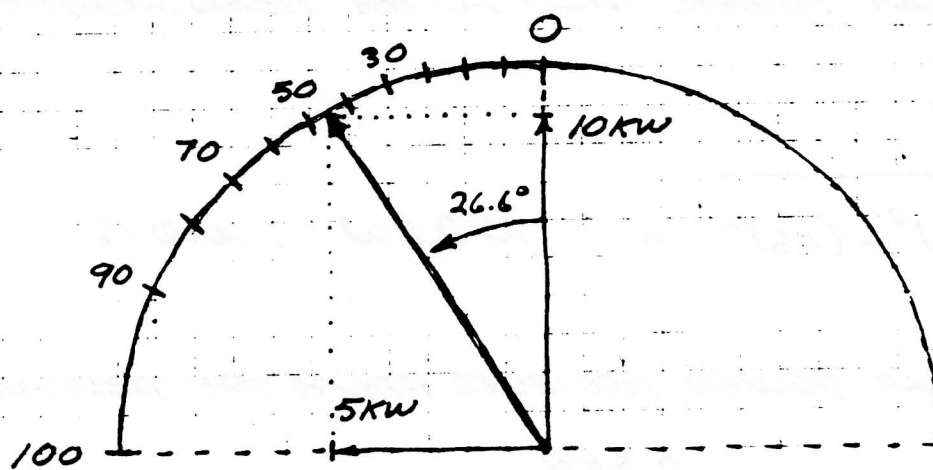
THUS THE WATTMETER INDICATES 89% OF THE TOTAL APPARENT POWER, P_o , THE VAR METER INDICATES 45% OF THE TOTAL APPARENT POWER.

$$\dot{P} = 89\% P_o + j45\% P_o = 100\% P_o \text{ AT } 26.6^\circ$$



POWER FACTOR

89%



INDUCTION FACTOR

45%

2) A TRANSFORMER COIL IS RECEIVING 10KW OF ACTIVE POWER BY INDUCTION FROM A NEARBY PRIMARY COIL AND DELIVERING IT TO A NON-INDUCTIVE LOAD AT 95% EFFICIENCY. THE COIL IS ~~CONSUMING~~ THUS DISSIPATING 0.5KW IN HEAT LOSSES. IN ADDITION, THE COIL IS CONSUMING 1.5 KW OF REACTIVE ENERGY IN ITS MAGNETIC LEAKAGE REACTANCE.

HENCE

$$P_i = -10\text{KW} + 0.5\text{KW} = -9.5\text{KW}$$

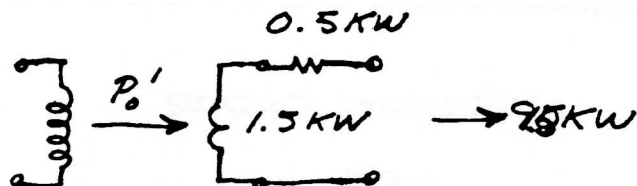
$$P_j = 1.5\text{KW}$$

$$P_o = \sqrt{(-9.5)^2 + (1.5)^2} = 9.6\text{KW}, \text{ AND IS}$$

THE APPARENT POWER FLOW IN THE TRANSFORMER COIL.

$$P_o' = \sqrt{(-10)^2 + (1.5)^2} = 10.2\text{KW}, \text{ AND IS}$$

THE APPARENT POWER RECEIVED FROM THE PRIMARY COIL.



THE POWER FACTOR OF THE TRANSFORMER COIL RECEIVING INDUCED ENERGY IS,

$$a = P_i / P_o = -9.5 / 9.6 = -98\%$$

THE INDUCTIVE FACTOR IS,

$$b = P_j / P_o = 1.5 / 9.6 = +16\%$$

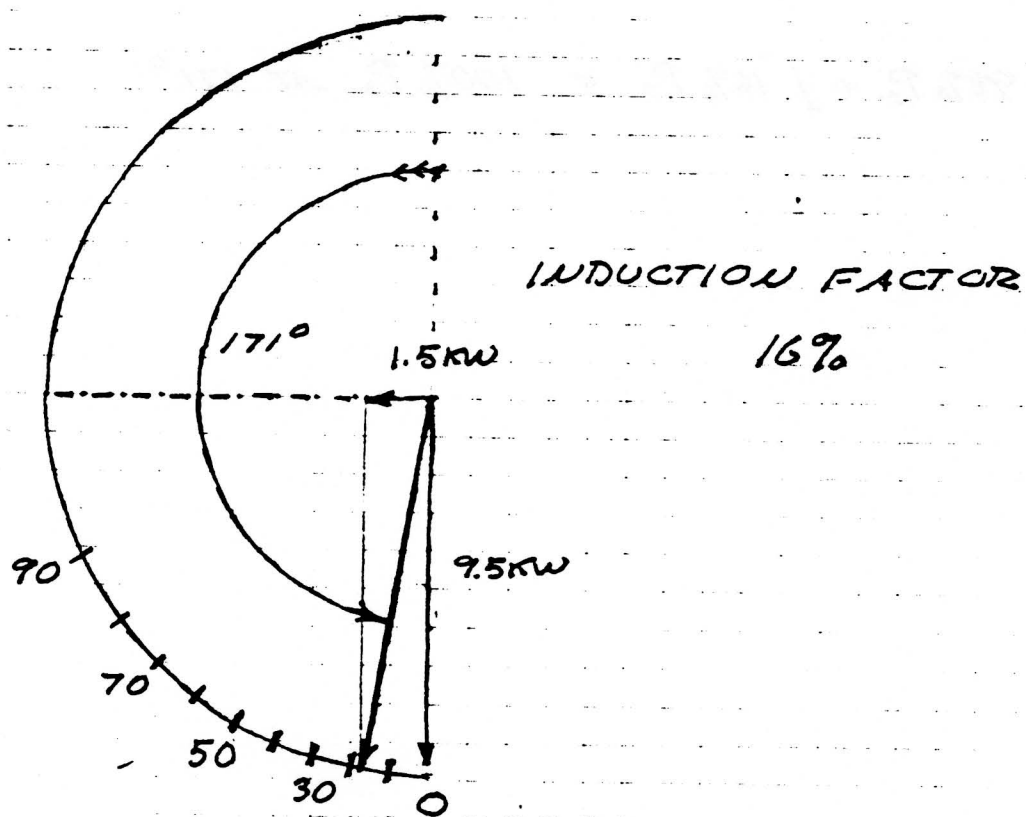
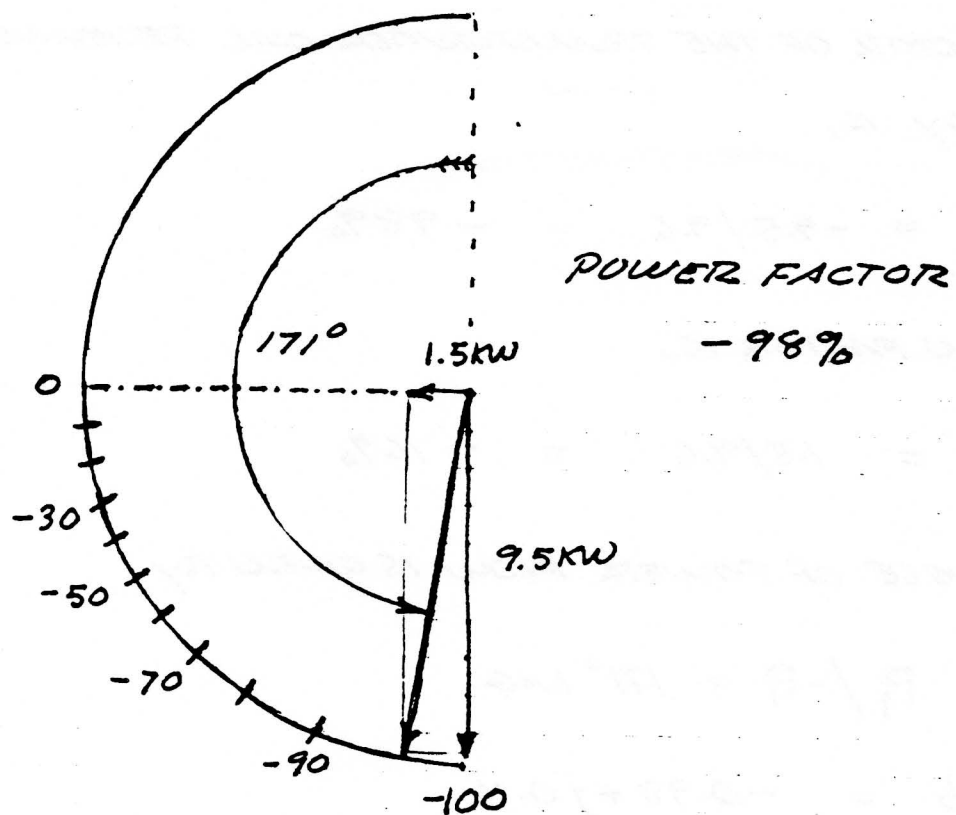
THE PHASE ANGLE OF POWER FLOW IS GIVEN BY

$$\theta_o = \tan^{-1} P_j / -P_i = 171^\circ \text{ LAG}$$

$$\gamma_o = a + jb = -0.98 + j0.16$$

THUS THE VECTORIAL POWER IS

$$\dot{P} = -98\% P_o + j 16\% P_o = 100\% P_o \text{ AT } 171^\circ$$



3) A SYNCHRONOUS MOTOR IS DELIVERING 200HP TO AN AIR COMPRESSOR. THE MOTOR IS BEING OVER EXCITED TO FACILITATE SYNCHRONOUS CONDENSER ACTION, THEREBY GENERATING 250 KW OF REACTIVE POWER,

HENCE

$$P_1 = 200\text{HP} = 150\text{KW} \quad \text{WATTMETER}$$

$$P_2 = -250\text{KW} \quad \text{VAR METER}$$

$$P_0 = \sqrt{150^2 + 250^2} = 293\text{KW} \quad \text{VOLTMETER X AMMETER}$$

$$a = P_1 / P_0 = 51\% \quad \text{ACTIVE ENERGY} \quad \text{POWER FACTOR METER}$$

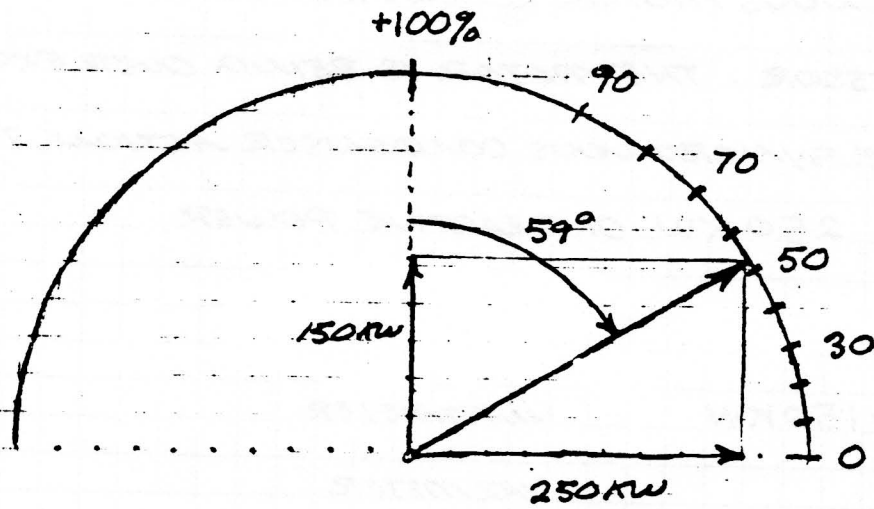
$$b = P_2 / P_0 = 85\% \quad \text{REACTIVE ENERGY} \quad \text{INDUCTION FACTOR METER}$$

$$\theta_0 = \tan^{-1} -P_2 / P_1 = 59^\circ \text{ LEAD}$$

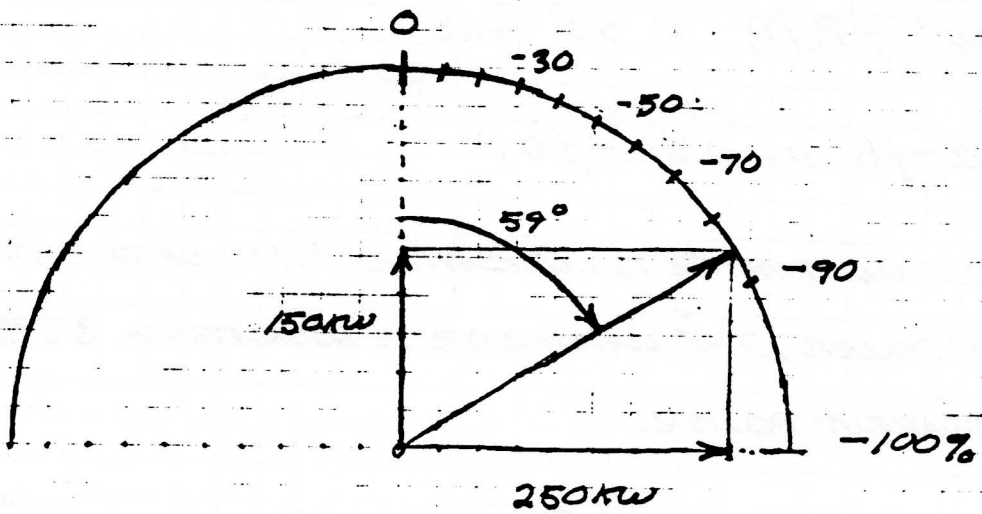
$$\gamma_0 = a - jb = 0.51 - j0.85$$

THUS, THE WATTMETER IS INDICATING 51% OF THE TOTAL APPARENT POWER, THE VAR METER IS INDICATING 85% OF THE TOTAL APPARENT POWER.

$$\vec{P} = 51\% P_0 - j85\% P_0 = 100\% P_0 \text{ AT } -59^\circ$$



POWER FACTOR 51%



INDUCTION FACTOR -85%

SUMMARY

- 1) FOR THE ALGEBRAIC REPRESENTATION OF A.C. POWER THE E.M.F. $\dot{E}$ AND M.M.F. $\dot{I}$ MUST BE EXPRESSED IN SYMBOLIC REPRESENTATION BY REAL AND IMAGINARY QUANTITIES, $A_1 \pm j A_2$.
- 2) THE VECTORS OF E.M.F. $\dot{E}$, AND M.M.F. $\dot{I}$ ROTATE IN OPPOSITE DIRECTIONS AS A RESULT OF THE CONSUMPTION OF M.M.F. COINCIDING WITH THE PRODUCTION OF E.M.F. DURING THE A.C. CYCLE.
- 3) THE EFFECTIVE IMPEDANCE Z AND EFFECTIVE ADMITTANCE Y ARE A RESULT OF THE ELECTRIC FIELD SURROUNDING THE CIRCUIT AND WITHIN THE MOLECULES OF THE CIRCUIT MATERIALS. IN ORDER FOR THESE VALUES TO REPRESENT THE VALUES MEASURED BY OHMMETERS, ETC., THE RATIO OF TRANSVERSE TO LONGITUDINAL FLOW MUST BE CONSIDERED.

- 4) ALTERNATING ELECTRIC POWER IS A RESULT OF TWO VECTORS OF OPPOSITE ROTATION, E AND I , THUS POWER PULSATES AT TWICE THE FREQUENCY OF VOLTS OR AMPERES.
- 5) A.C. POWER CONSISTS OF TWO COMPONENTS, THE REAL ACTIVE ENERGY, AND THE IMAGINARY REACTIVE ENERGY.
- 6) A.C. POWER CAN BE REPRESENTED AS A COMPLEX QUANTITY WITH REAL AND IMAGINARY COMPONENTS IN THE SAME MANNER AS E OR I THEMSELVES.
- 7) REACTIVE POWER IS AS IMPORTANT AS REAL POWER FOR THE TRANSMISSION AND UTILIZATION OF A.C. ENERGY.
- 8) THE POWER FACTOR IS USED AS A CORRECTION FACTOR APPLIED TO THE WATTMETER READING TO GIVE THE QUANTITY OF ^{REAL} ACTIVE POWER FLOW. THE INDUCTION FACTOR IS USED AS A CORRECTION FACTOR APPLIED TO THE ^{VAR} ~~WATTMETER~~ READING TO GIVE THE QUANTITY OF ACTIVE POWER FLOW. BOTH SERVE AS CORRECTION FACTORS TO THE VOLTAMPERE READING TO GIVE THE QUANTITY OF ACTIVE AND REACTIVE POWER RESPECTIVELY.

9) THE VECTOR SUM OF THE POWER FACTOR AND THE INDUCTION FACTOR IS THE WAVE FACTOR OF THE A.C. CIRCUIT. THE WAVE FACTOR GIVES THE DIRECTION OF POWER FLOW.

10) IN AN A.C. CIRCUIT CONSUMING ACTIVE ENERGY ONLY, THE E.M.F. $\dot{E}$ AND M.M.F. $\dot{I}$ ARE IN PHASE CONJUNCTION, (0°).

11) IN AN A.C. CIRCUIT ~~CONSUMING~~ PRODUCING ACTIVE ENERGY ONLY, THE E.M.F. $\dot{E}$ AND M.M.F. $\dot{I}$ ARE IN PHASE OPPOSITION, (180°).

12) IN AN A.C. CIRCUIT CONSUMING REACTIVE ENERGY ONLY, THE E.M.F. $\dot{E}$ AND THE M.M.F. $\dot{I}$ ARE IN PHASE LAG QUADRATURE, ($+90^\circ$).

13) IN AN A.C. CIRCUIT ~~CONSUMING~~ PRODUCING REACTIVE ENERGY ONLY, THE E.M.F. $\dot{E}$ AND THE M.M.F. $\dot{I}$ ARE IN PHASE LEAD QUADRATURE, (-90°).

14) THE FOUR CLASSES OF POWER ARE REPRESENTED BY THE ALGEBRAIC SYMBOL

$$1^n = \sqrt[4]{+1} = +1, +j, -1, -j$$

AND THUS THE CYCLE OF ALTERNATING CURRENT IS DIVIDED INTO FOUR QUARTERS, OR QUADRANTS

I, FIRST QUARTER CYCLE; CONSUMPTION OF ACTIVE AND OF REACTIVE ENERGIES.

II, SECOND QUARTER CYCLE; PRODUCTION OF ACTIVE ENERGY AND CONSUMPTION OF REACTIVE ENERGY.

III, THIRD QUARTER CYCLE; PRODUCTION OF ACTIVE AND OF REACTIVE ENERGIES.

IV, FOURTH QUARTER CYCLE; CONSUMPTION OF ACTIVE ENERGY AND PRODUCTION OF REACTIVE ENERGY.

15) THE WATTMETER, POWER FACTOR METER AND INDUCTION FACTOR METER, TOGETHER PROVIDE A COMPLETE REPRESENTATION OF THE A.C. WAVE

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